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An investigation into the RCCI engine operation under low load and its achievable operational range at different engine speeds

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ABSTRACT

Reactivity controlled compression ignition (RCCI) is demonstrated as a promising combustion strategy to achieve high efficiency and clean combustion. However, less effort has been devoted to examine the achievable RCCI operational range over a wide range of engine speed. In addition, previous studies have found that superior EGR rate and high diesel/gasoline fuel ratio are required to ease the extension of the low-load operating range of RCCI regime. Even then, relatively high CO and HC (unburned hydrocarbon) emissions and the accompanying fuel con-sum ption penalty still remain a problem to be resolved. Therefore, in this work the potential of diesel-fueled LTC to achieve simultaneously low NOx and soot emissions while maintaining high thermal efficiency at low load (IMEP ≈0.23–0.26 MPa) is investigated and compared with the gasoline/diesel RCCI strategy. The results show that the diesel LTC operation can yield slightly higher soot and NOx emissions (soot: 0.002 g/kW h, NOx: 0.446 g/kW h), but CO and HC emissions as well as the fuel consumption are much lower than the RCCI strategy, implying the diesel LTC regime may be more suitable for low-load operations. In addition, the RCCI operational range at speeds ranging from 900 to 2500 r/min is determined, the results show that the maximum achievable load (IMEP) increases with an increase in speed, and a maximum IMEP of 1.2 MPa can be achieved at an engine speed of 2300 r/min. Ultra-low NOx and soot emissions (soot < 0.003 g/kW h, NOx < 0.4 g/kW h) can be achieved under the maximum loading conditions at each speed investigated. However, high levels of CO and HC emissions still remain a big problem to be solved. The lowest fuel consumption (168.6 g/kW h) occurred at an engine speed of 1900 r/min with an EGR rate of 56%, and the corresponding indicated thermal efficiency is up to 50%. In addition, intake boosting can be very effective for expanding the RCCI operating range at low engine speed (900 r/min), but excessive pressure rise rates could become problematic with increased amount of fuel injection.

1. Introduction

With concerns about limited petroleum supplies and global warming driving the demand for fuel-efficient engines, interest in diesel engines is stronger than ever [1]. It is well known that diesel engines have the highest thermal efficiency among various engines ever developed for transportation purposes, mainly due to their high compression ratios and lack of throttling losses. Unfortunately, owing to the traditional trade-off relationship between soot and NOx (nitrogen oxides) emissions observed in conventional jet-mixing controlled diesel combustion, it appears unlikely that diesel engines can meet the increasingly stringent emission regulations without the usage of expensive after-treatment devices. To meet the requirements for further reduction in exhaust emissions while maintaining diesel-like cycle thermal

Abbreviations: RCCI, reactivity controlled compression ignition; LTC, low temperature combustion; EGR, exhaust gas recirculation; PCCI, premixed charge compression ignition; LTC, low temperature combustion; BMEP, brake mean effective pressure; CN, cetane number; IMEP, indicated mean effective pressure; SOC, start of combustion; SOI, start of injection; CA, crank angle; CA90, crank angle where 90% of the total heat release occurs; ATDC, after top dead center; CA50, crank angle where 50% of the total heat release occurs; HCCI, homogeneous charge compression ignition; CA, crank angle; NOx, nitrogen oxides; CO, carbon monoxide; UHC, unburned hydrocarbon; MPRR, maximum pressure rise rate; ISFC, indicated specific fuel consumption; COV_{IMEP}, the coefficient of variation of the indicated mean effective pressure; TDC, top dead center.

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efficiency, many researchers are turning their attention to alternative regimes of compression ignition combustion, such as homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), stratified charge compression ignition (SCCI) and low temperature combustion (LTC), etc., within which reactivity controlled compression ignition (RCCI) has received more and more attention in the engine combustion community and become a focus of engine research around the world in recent years.

RCCI is a dual-fuel combustion strategy that utilizes in-cylinder fuel blending with at least two fuels with different reactivity to control and optimize the combustion phasing, duration and magnitude [2]. A considerable amount of research on RCCI has taken place in the last few years and on several simultaneous fronts. To be specific, some previous studies have demonstrated the potential of the RCCI concept in a wide range of engine speed and engine loads. A previous study by Benajes et al. [3] examined the potential of RCCI to reach Euro VI NOx levels and ultra-low soot emissions from idle to full-load and engine speed from 900 to 1800 r/min. They found that high soot levels, consequence of the progressive delay in diesel injection timing to avoid excessive pressure rise rate as load is increased, limited the RCCI engine operating map to 50% load at a compression ratio of 14.4, while the NOx emission showed an obvious dependency on engine speed. Later, Molina et al. [4] investigated the effects of different engine operating variables over RCCI combustion and further suggested suitable strategies for extending the RCCI operating range from low to full load in a heavy-duty single-cylinder research engine. Multi-dimensional computational fluid dynamics (CFD) simulations were also performed to analyze engine performance and emissions. Moreover, there have been a few research works published regarding the superiority of the RCCI operation strategy over other combustion regimes, such as HCCI, PPC (partially premixed combustion) and conventional diesel combustion (CDC). For instance, Dempsey et al. [5] performed a comprehensive comparison of RCCI, PPC and HCCI to evaluate the sensitivity of these strategies to intake conditions and the ability to control the observed sensitivities with the fuel injection strategy. The three combustion regimes were first operated using the primary reference fuels: *n*-heptane and *iso*-octane to remove fuel effects. The results showed that both HCCI and RCCI had a very pronounced ability to target a given CA50 through slight changes of the global fuel reactivity in the combustion chamber. Single fuel PPC operated on PRF94 (nC_7H_{16}/iC_8H_{18}, 4/96% by volume) demonstrated some level of control, but over a much wider range of premixed fuel percentage. When the premixed fuel percentage was low, the NOx emissions began to increase due to the existence of high equivalence ratio regions at the onset of combustion. PPC and RCCI displayed very similar trends with commercial pump diesel and gasoline fuel compared to the PRFs. However, pump fuel RCCI showed less controllability and increased NOx emissions compared to operation with the primary reference fuels due to the reduced reactivity gradient between the premixed and direct injected fuels. In another research, direct comparisons were made by Kokjohn et al. [6] between RCCI operation and conventional diesel operation at the 0.9 MPa IMEP (indicated mean effective pressure) operating point. Especially, the authors also implemented the KIVA-3V CFD code to capture the physics of the RCCI combustion process and to study the sources of the efficiency benefits compared to CDC. On the basis of the new findings from these previous studies, there has been some work done in the near past on the exploration of different injection strategies at various engine loads and their impact on the combustion and emission characteristics of RCCI operations. Ma et al. [7] investigated the influence of both single and double injection strategies with different injection timings in a RCCI engine. Comparisons were made among four injection scenarios namely E-single (early injection timing of single), L-single (late injection timing of single), E-SOI2 (early second injection timing of double) and L-SOI2 (late second injection timing of double). The results showed that the combustion process with E-single injection scenario exhibited typical HCCI combustion patterns with a small peak of low-temperature oxidation preceding a large peak of high-temperature oxidation with little diffusion combustion. While for the double-injection strategy, the first diesel injection determined the reactivity of mixture; the second injection of diesel played a larger role in the formation of reactivity of stratification. As for fuel consumption, the ESOI-2 case demonstrated superior features. However, the L-SOI2 case is advantageous in reducing pressure rise rate. The E-SOI2 injection scenario might be a good injection control strategy at middle load, while L-SOI2 could be useful in expanding high-load limits for RCCI operations. Furthermore, in order to overcome the restriction on the requirement of two fuel systems for RCCI operation which could lead to decreased market acceptance, some research works in the literature have focused on investigating the possibility of using a single fuel stock with the addition of a small concentration of a highly reactive chemical to the only fuel used to serve as a cetane number (CN) improver to ease RCCI operation. Hanson et al. [8] compared the results between both the “single fuel” and the “dual-fuel” strategies. They used gasoline mixed with the CN improver 2-EHN (2-ethyl-hexyl nitrate) at a doping percentage of 3.5% by volume in the direct injection fuel stream, and un-doped gasoline via port fuel delivery. The results showed that the combustion phasing was found to be easily controlled by adjusting the ratio of port-fuel injection of gasoline to direct injection of gasoline doped with 2-EHN. In the “single fuel” case, the high-temperature heat release was faster than the “dual-fuel” strategy, and significant differences were also observed in the low-temperature heat release due to the addition of 2-EHN. Since gasoline typically does not exhibit a two stage heat release, the low-temperature reactions occurred from the decomposition of the 2-EHN in the direct injection fuel stream. Furthermore, the authors also investigated low-load RCCI operation (2 and 4.5 bar gross IMEP) at speeds ranging from 800 to 1700 r/min by using both dual fuel and single fueling strategies. In the speed sweep, the single fuel strategy showed similar trends in combustion and high-temperature heat release duration at constant combustion phasing to that of the dual fuel test results. The single-fuel strategy showed similar HC, CO and NOx trade-offs as the dual-fuel tests. In a later study by Kaddatz et al. [9], they performed similar research on a light-duty diesel engine was performed to investigate RCCI combustion by using E10 (90% gasoline and 10% ethanol by volume) doped with 3% 2-EHN (by volume) as the high-reactivity fuel and compared with diesel/gasoline RCCI operations. More recently, Splitter et al. [10] explored the effect of direct-injected fuel properties on gross thermal efficiency with respect to intake temperature and pressure, and equivalence ratio as function of engine operating parameters, such as fuel reactivity, CA50 (crank angle of 50% total heat release) and engine load. In this work the engine was port fueled with E85 (15% gasoline and 85% ethanol by volume) for the low reactivity fuel and direct injected with either #2 ultra-low sulfur diesel or 91 anti-knock Index gasoline doped with 3% 2-EHN for the high reactivity fuel. The reactivity of the 2-EHN enhanced fuel has been correlated to an anti-knock index of approximately 56 and a CN number of approximately 28.

It is worth noting that all of the research works mentioned above were performed at steady-state operating conditions, while most vehicles operate under constantly changing engine speeds and loads and the engine transient performance cannot be accurately reflected by steady-state engine calibrations [11–13]. In view of this, a few recent research works and development efforts on RCCI are underway with a focus on investigating RCCI engine transient performance. For example, Wu et al. [14] studied